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F. MARIANI

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Evidence for the Effect of Corpuscular Radiation on the Ionosphere

F. Mariani[1] (Rome U.)

Istituto Di Fisica, Universita Di Roma, Commissione Italiana Per Le Ricerche Spaziali Del C.N.R., Roma

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ABSTRACT

The correlation of maximum electron density in the F region at noon with solar activity is investigated for both long-term and month-to-month variations, in data for 1937–57 from all existing observatories. On the basis of noon-equilibrium between electron loss and ion production by solar radiation, an ionizing effect, strongly dependent on solar activity and peaked at latitudes of 55 to 65 deg is shown to exist.

This latitudinal variation suggests a corpuscular origin of the effect. The possible source of a corpuscular flux is discussed. The energy of the ionizing particles is in the range of kev. Quantitative evidence is given that Van Allen belts could be an important, or possibly the main, source.

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1. Introduction

Recent studies (Mariani, 1959 and 1960, here indicated as M1 and M2) on the variations of electron density distribution in the $F2$ layer suggest some latitudinal and 11-yr variations of the solar ultraviolet radiation. The interpretation of these results is rather difficult because the experimental data can be affected by other than solar causes (local variations of atmospheric temperature and winds, diffusion, etc.). Moreover, in the study of long series of ionospheric data, one cannot completely eliminate the "regular" effect due to the seasonal variation of zenith distance of the sun. Because of these difficulties, it is desirable to apply statistical methods to the data of all existing observatories. Local irregularities and systematic effects in a number of observatories are then easily recognizable, and some general conclusions can be drawn.

It is the purpose of this paper to apply a statistical analysis to all ionospheric data collected in the two 11-yr periods, 1937–1947 and 1947–1957.

2. Experimental data and method of analysis

In this study, we used the monthly median values of $foF2$ at noon for about 70 observatories, listed in Table 1, whose data are published by the Central Radio Propagation Laboratory of the National Bureau of Standards or directly by the observatories.

For indicators of solar activity, we used the monthly means of final sunspot numbers and of sunspot areas, published by the observatories of Zurich and Washington, respectively; the monthly mean areas of hydrogen filaments and hydrogen and calcium flocculi, deduced from the character numbers published by the Astrophysical Observatory of Arcetri; and the monthly values of heliographic distribution of chromospheric activity published by the observatory of Meudon. Details on the above parameters of solar activity are given elsewhere. The method of analysis is the same as that used in the previous papers M1 and M2.

Following is a list of symbols:

N = monthly median values of $(foF2)^2$, in $(\mathrm{Mc/s})^2$
N_{12} = seasonal (twelve-month) variation of N
R = monthly mean of sunspot number
A_R = monthly mean of sunspot area
A_F = monthly mean of hydrogen-filament area
$A_{\Phi H}$ = monthly mean of hydrogen-flocculi area
$A_{\Phi Ca}$ = monthly mean of calcium-flocculi area
A_i = one of the above quantities R, A_R, A_F, etc.

When the above symbols have a bar (for example $\bar{N}$, $\bar{A}_F$, etc.) they represent the calculated corresponding value for the long-term (11-yr) variation.

3. The correlation of $F2$ layer maximum electron density at noon with solar activity

We considered for each observatory simple and double linear regressions of the maximum electron density at noon with one solar parameter A_i (or two different parameters, A_i and A_j) expressed in the analytical form

$$\bar{N}=\bar{N}_0(1+\bar{\alpha}_i\bar{A}_i) \qquad (1)$$

$$\bar{N}=\bar{N}_0(1+\bar{\beta}_i\bar{A}_i+\bar{\gamma}_j\bar{A}_j) \qquad (2)$$

for long-term variations or,

$$N-N_{12}=(N-N_{12})_0(1+\alpha_iA_i) \qquad (3)$$

$$N-N_{12}=(N-N_{12})_0(1+\beta_iA_i+\gamma_jA_j) \qquad (4)$$

for actual month-to-month variations.

[1] Now at Goddard Space Flight Center, Greenbelt, Md., as NAS-NASA Senior Post-doctoral Research Associate.

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TABLE 1. Locations of observatories used, in geomagnetic and geographical coordinates.

Observatory	Geomag. Coordinates Lat.	Long. (East)	Geograph. Coordinates Lat.	Long. (East)
Clyde	82N	1	70N	291
Resolute Bay	82N	289	75N	265
Godhavn	80N	32	69N	306
Baker Lake	74N	315	64N	264
Narsassuaq	71N	38	61N	315
Reykjavik	70N	71	64N	338
Churchill	69N	323	59N	266
Point Barrow	68N	241	71N	203
Tromso	67N	117	70N	19
Kiruna	65N	116	68N	20
Fairbanks (Col.)	65N	256	65N	148
Anchorage	61N	258	61N	210
Inverness	61N	83	57N	356
Olso	60N	11	60N	10
Winnipeg	60N	323	50N	263
Uppsala	59N	106	60N	18
St. John	59N	21	48N	307
Prince Rupert	58N	283	54N	230
Ottawa	57N	351	45N	284
Leningrad	56N	118	60N	31
Slough	54N	83	51N	359
De Bilt	54N	89	52N	5
Lindau	52N	94	52N	10
Moscow	50N	121	55N	37
Freiburg	50N	90	48N	8
Washington	50N	350	39N	283
Poitiers	49N	82	47N	0
Schwarzenburg	48N	89	47N	7
Adak	47N	240	52N	183
Graz	47N	97	47N	15
Tomsk	45N	160	56N	85
San Francisco	44N	298	37N	238
White Sands	41N	316	33N	253
Baton Rouge	41N	334	30N	269
Casablanca	38N	69	34N	352
Wakkanai	35N	206	45N	142
Alma Ata	33N	152	43N	77
Portorico	30N	2	18N	293
Akita	29N	205	40N	140
Tokyo	25N	206	36N	140
Yamagawa	21N	198	31N	131
Dakar	21N	55	14N	343
Maui	21N	268	21N	203
Panama	21N	348	9N	280
Delhi	19N	149	29N	77
Okinawa	15N	196	26N	128
Formosa	14N	189	25N	121
Ibadan	11N	75	7N	4
Bombay	10N	144	19N	73
Djibouti	7N	114	11N	43
Baguio	5N	189	16N	121
Madras	3N	150	13N	80
Guam	3N	212	13N	145
Tiruchy	1N	148	11N	79
Huancayo	0.6S	354	12S	285
Leopoldville	3S	84	4S	15
Singapore	10S	173	1N	104
Rarotonga	21S	274	21S	200
Buenos Aires	23S	9	35S	302
Tananarive	24S	113	19S	48
Johannesburg	27S	91	26S	28
Capetown	33S	80	34S	18
Brisbane	36S	227	27S	153
Falkland Is.	40S	9	52S	302
Watheroo	42S	186	30S	116
Canberra	44S	225	35S	149
Christchurch	48S	253	44S	173
Hobart	52S	225	43S	147
Decepcion	52S	7	63S	299
Port Lockroy	53S	4	65S	297
Campbell Is.	57S	253	53S	169
Macquarie Is.	61S	243	54S	159
Terre Adelie	75S	231	67S	140

The quantities $\bar{N}_0$ and $(N-N_{12})_0$ represent the values deduced from the secular variation and from the month-to-month variation $N-N_{12}$ at minimum solar activity ($A_i=0$), i.e., the electron density for an absolutely quiet sun.

In M1 we found for the years 1947–1954 a remarkable dependence of $\bar{N}$ and $N-N_{12}$ upon the areas A_F of hydrogen filaments, after eliminating the dependence upon the sunspot number; a rough confirmation of this result was obtained in M2 from the few available data corresponding to the years 1938–1944. Comparison of results for northern and southern hemispheres indicated a noticeable asymmetry in the correlations with A_F, and in any case a clear latitudinal effect with a minimum at the equator.

In order to improve the above results and to see if they also apply to other phases of the solar cycle, we have since investigated the correlations of electron densities with as many solar parameters as possible. First we calculated the simple correlations of the electron densities with the sunspot number R, the areas A_R, A_F, $A_{\Phi H}$ and $A_{\Phi Ca}$; later we looked for possible effects of the position of the perturbation centers on the solar disk by investigating some correlations with the Meudon filament activity.

The overall results of such calculations give a conclusive confirmation of a latitudinal effect of the regression coefficients in the four intervals 1938–1944, 1944–1947, 1947–1954, 1954–1957 which correspond alternately to decreasing and increasing phases of the solar cycle. For a few observatories we could obtain only qualitative rather than quantitative information, because of insufficient data. These cases are not included in the quantitative results we give in the next sections.

We consider separately the cases of the long-term and month-to-month variations.

3.1 The case of long-term variation $\bar{N}$. The principal results are given in Figs. 1, 2 and 3, in which we show the quantities $\bar{N}_0$ and $\bar{\alpha}_i$ defined by (1) for the simple correlations of $\bar{N}$ with the sunspot number $\bar{R}$ (Fig. 1), the area $\bar{A}_F$ (Fig. 2) and the areas $\bar{A}_{\Phi H}$ and $\bar{A}_{\Phi Ca}$ (Fig. 3), respectively. In all the diagrams we indicate on the abscissae an "effective" latitude defined as the arithmetical mean of geographical and geomagnetic latitudes. As found earlier in M1, such a choice leads to some reduction of minor irregularities in the distribution of the points on the graphs and takes into some account the dependence of the electron density upon both the geographical and geomagnetic coordinates. In the left half of each figure we show the values of $\bar{N}_0$, in the right half the values of $\bar{\alpha}_i$. The amplitude of the standard errors is indicated for all the calculated points.

A first interesting feature is the rather symmetrical distribution of $\bar{N}_0$ in the two hemispheres for latitudes greater than 20 deg. In the tropical latitude belt $\bar{N}_0$ exhibits two relative maxima; the maximum in the northern hemisphere is rather localized while the posi-

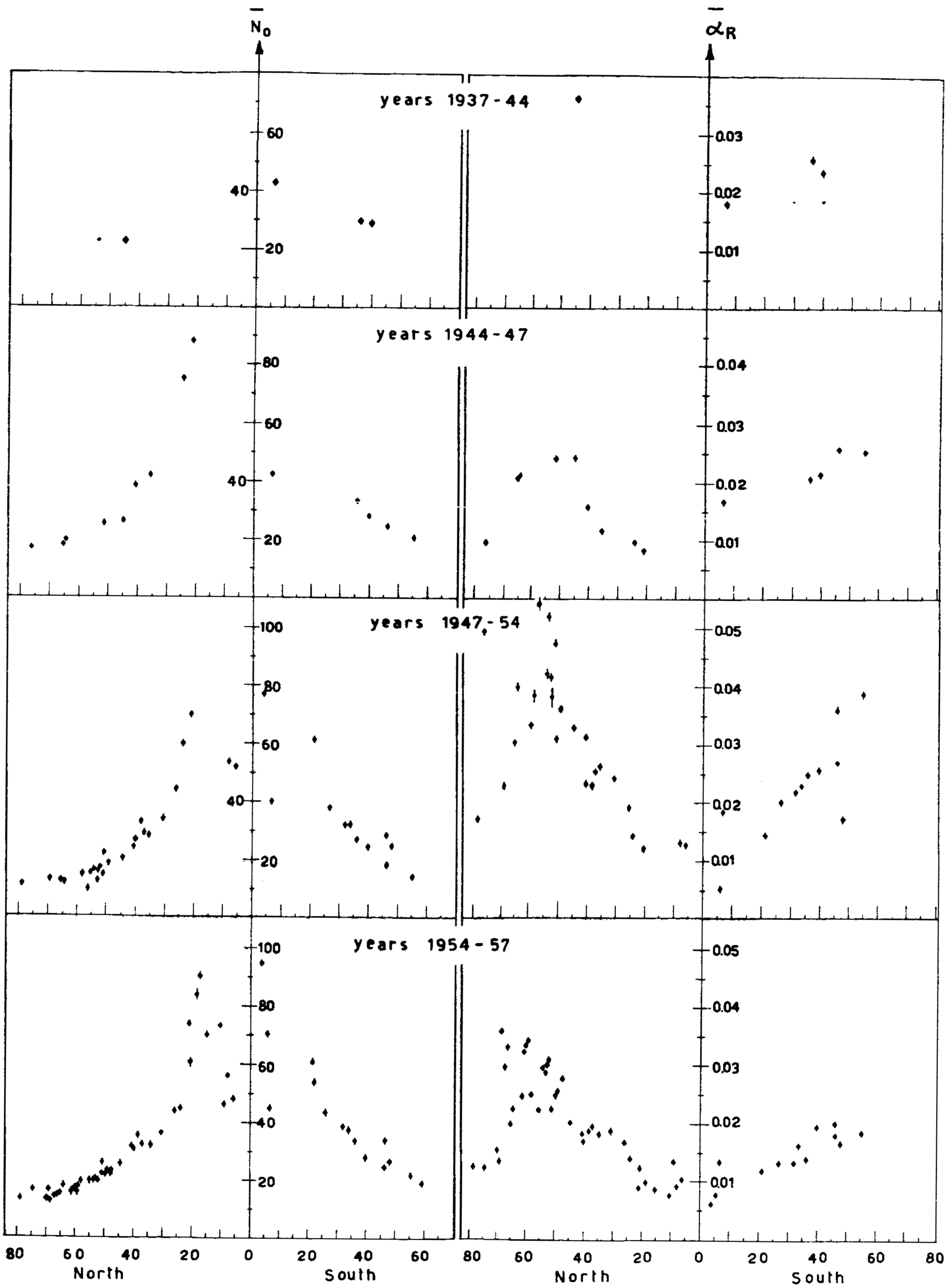

FIG. 1. Correlation of the long-term variation $\bar{N}$ and $\bar{R}$. The abscissae, in this figure and in the following (Figs. 2, 3, 5, 6, 7 and 8) is the "effective" latitude as defined in Section 3.1.

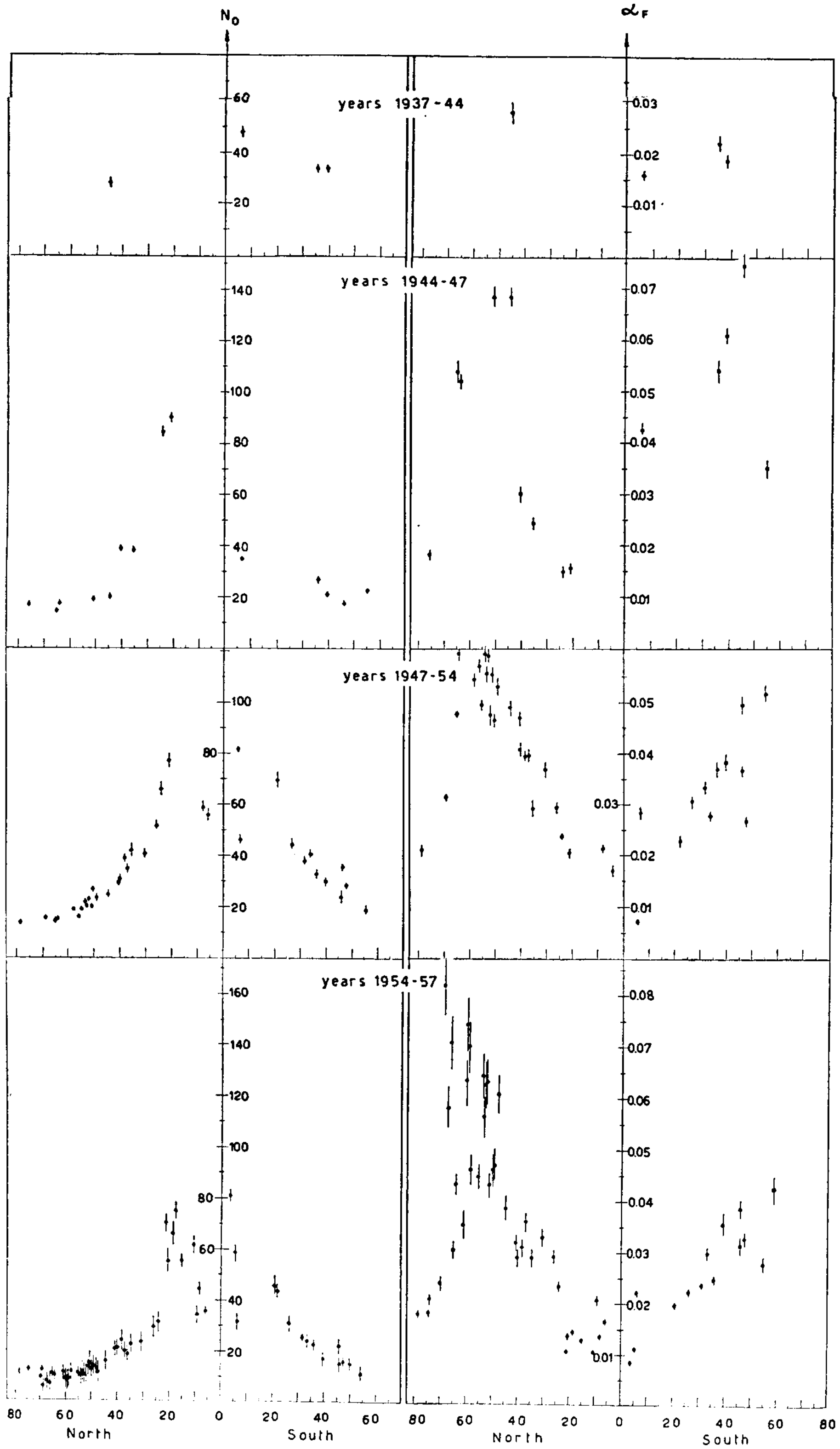

FIG. 2. Correlation of the long-term variation in $\bar{N}$ and $\bar{A}_F$.

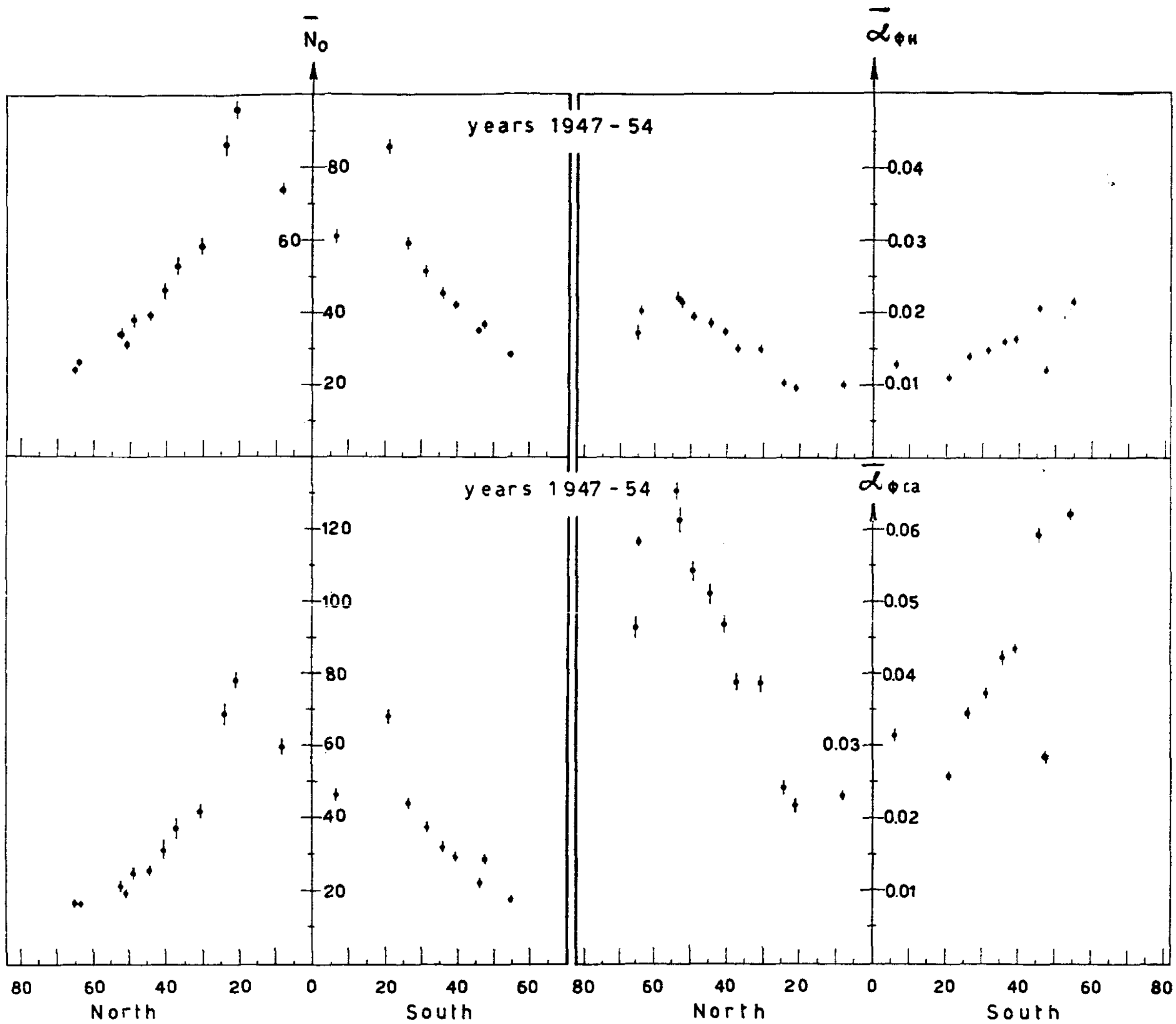

FIG. 3. Correlation of the long-term variation in $\bar{N}$ and $\bar{A}\phi_H$ (upper graphs) and $\bar{N}$ and $\bar{A}\phi_{Ca}$ (lower graphs).

tion of the southern hemisphere maximum is not as clear, because of the lack of sufficient experimental data at those latitudes. The occurrence of such maxima in tropical regions is a well known feature of the $F2$ layer.

We can also compare the latitudinal variation of $\bar{N}_0$ and the annual mean of cos χ_{noon}, where χ_{noon} is the noon zenith distance of the sun. Values of cos χ_{noon} are proportional to the noon ionization intensity and, for the $F2$ layer, also approximately proportional to the noon electron density. These values have been calculated (Fig. 4), taking into consideration the sphericity of the earth and sunlight at ionospheric levels (even during polar winter at noon in all the northern observatories). By use of proper normalization factors, we obtain a rather good fit of the experimental values $\bar{N}_0$ with the annual mean of cos χ_{noon} for latitudes higher than 30–35 deg.

Some anomalous values are present in the latitudinal distribution of $\bar{N}_0$, in particular the rather high values at Huancayo and Leopoldville, which are at or very close to the geomagnetic equator. Generally, as mentioned earlier, local conditions (such as upper atmospheric winds, anomalous temperature or concentration distribution) can influence the electron density. At this stage, then, we try to give a physical meaning to the general behavior rather than to some particular anomaly, which must await a more refined theory. In the particular case of equatorial data, for example, we recall that the geomagnetic field also exhibits an anomalous behavior on the geomagnetic equator, because of the equatorial electrojet at ionospheric levels.

We conclude that the values $\bar{N}_0$, for latitudes higher than 30–35 deg are a rather good index of the steady ultraviolet radiation at $F2$ levels.

If we now take into account the latitudinal variation of the regression coefficients $\bar{\alpha}_i$, assuming a dependence of $\bar{N}$ on the solar activity as given in (1), we would expect, within the statistical and experimental errors, constant values at all latitudes. This is not the case, however; a remarkable latitudinal effect is apparent.

A first interesting feature appearing in this latitudinal variation of the coefficients $\bar{\alpha}_i$ is an appreciable difference between their values in the northern and southern hemispheres, when we consider the correlation of $\bar{N}$ with $\bar{R}$ or $\bar{A}_F$. However, this is not the case for correlations with $\bar{A}_{\Phi H}$ or $\bar{A}_{\Phi Ca}$. The existence of a difference between the two hemispheres was already shown in M1 for the years 1947–1954. However, it may be only apparent, due to the particular solar parameters used in M1. Actually, the areas $\bar{A}_{\Phi H}$ and $\bar{A}_{\Phi Ca}$ may be a better index of solar activity than are the parameters $\bar{R}$ and $\bar{A}_F$ used in M1.

The most surprising feature of the latitudinal effect is the sharp maximum of $\bar{\alpha}_i$ at latitudes of 55–60 deg. At first sight, an increase of $\bar{\alpha}_i$ with latitude could be due to the decreasing values of $\bar{N}_0$. Such an effect can to some extent affect the variation of $\bar{\alpha}_i$. However it does not seem to be the determining factor, since at northern latitudes higher than 60 deg, $\bar{\alpha}_i$ first decreases remarkably and very steeply and then recovers to the equatorial values. For extreme southern latitudes the decrease of $\bar{\alpha}_i$ cannot be checked because of the lack of data; only its increase to 55 deg is observed.

A simple physical explanation of the above latitudinal effect can be given in terms of two superimposed effects. The first is a variation of ultraviolet radiation within the solar cycle, which is present in all places. The other effect is a latitudinal variation in corpuscular radiation directly or indirectly coming from, or influenced by, the sun. If this is the case, one can study the latitudinal variation of the absolute "corpuscular" effect.

We can write equation (1) in the form

$$\bar{N}=\bar{N}_0[1+a_i\bar{A}_i]+\bar{N}_0(\bar{\alpha}_i-a_i)\bar{A}_i, \qquad (5)$$

where the first term represents the "ultraviolet" effect and the last one the "corpuscular" effect; the quantity a_i is assumed to be independent of latitude. A possible value of a_i may be the mean of the $\bar{\alpha}_i$ values for tropical latitudes, which is practically the same as that for very high latitudes.

A clear latitudinal effect is again apparent not only in $\bar{\alpha}_i-a_i$, but, above all, in $\bar{N}_0(\bar{\alpha}_i-a_i)$. This last feature gives further evidence of a latitude dependence of the absolute intensity of the "corpuscular" effect. For reasons of brevity we do not give diagrams of $\bar{N}_0(\bar{\alpha}_i-a_i)$; we will rather consider the correlations of month-to-month variation which we study in the next section and which, from the physical point of view, are much more significant.

It should be emphasized that the $\bar{\alpha}_i$ distribution has its maximum at lower latitudes than the auroral zone; the lines of force between the geomagnetic latitudes 30 and 65 deg cross the equatorial plane at geocentric distances of about 1.4 and 5.5 earth's radii, i.e. at heights of 2500 and 29,000 km above the ground. At least from a qualitative point of view, one could think in terms of some connection between corpuscular ionospheric effects and Van Allen radiation belts. We shall consider this point later in Section 4.

The double correlation with $\bar{R}$ and $\bar{A}_F$, defined by (2) was also tested, for the years 1944–1947 and 1954–1957; the same double correlation with $\bar{R}$ and $\bar{A}_F$, for the years 1947–1954, having been already considered in *M*1. For the latter time interval a latitudinal constancy of $\bar{\beta}_R$ and a latitudinal variation of $\bar{\gamma}_F$ was established; such a feature is not confirmed during the two increasing phases of the solar cycle, so that it must be considered as a non-permanent feature.

3.2 The case of the month-to-month variation $N-N_{12}$. This case is more expressive from the physical point of view, because it takes into account the actual unsmoothed month-to-month variation of both electron density and solar parameters.

The results of our calculations are shown in Figs. 5, 6 and 7. In this case, obviously, the statistical errors are about an order of magnitude greater than in the case of the long-term variation. The essential features of the behavior of $(N-N_{12})_0$ and α_i are clear. The statistical improvement with a sufficient amount of ionospheric data can be seen by considering the 11-yr period 1947–1957. The mean values of α_i for correlations with monthly values of R and A_F are again greater in the northern than in the southern hemisphere, while this is

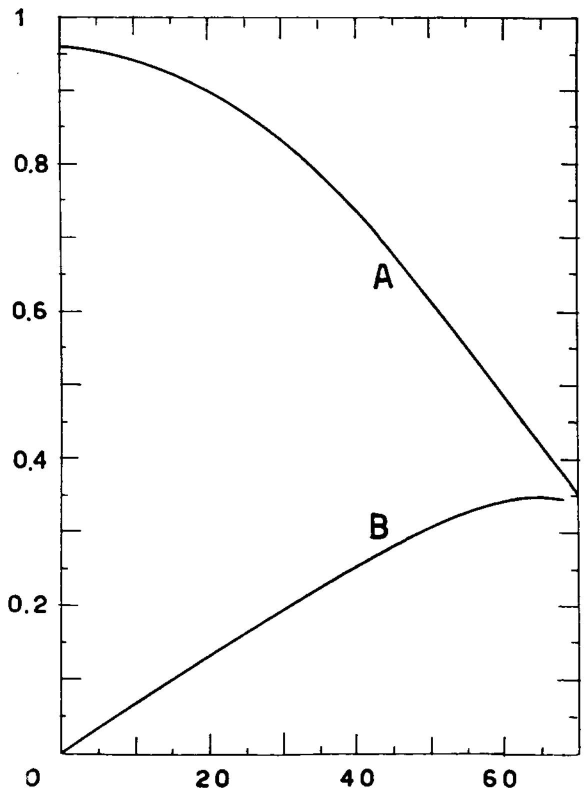

FIG. 4. Latitudinal variation of annual mean of cos χ_{noon} (curve A) and of the amplitude of its seasonal variation (curve B). The abscissa is the geographical latitude.

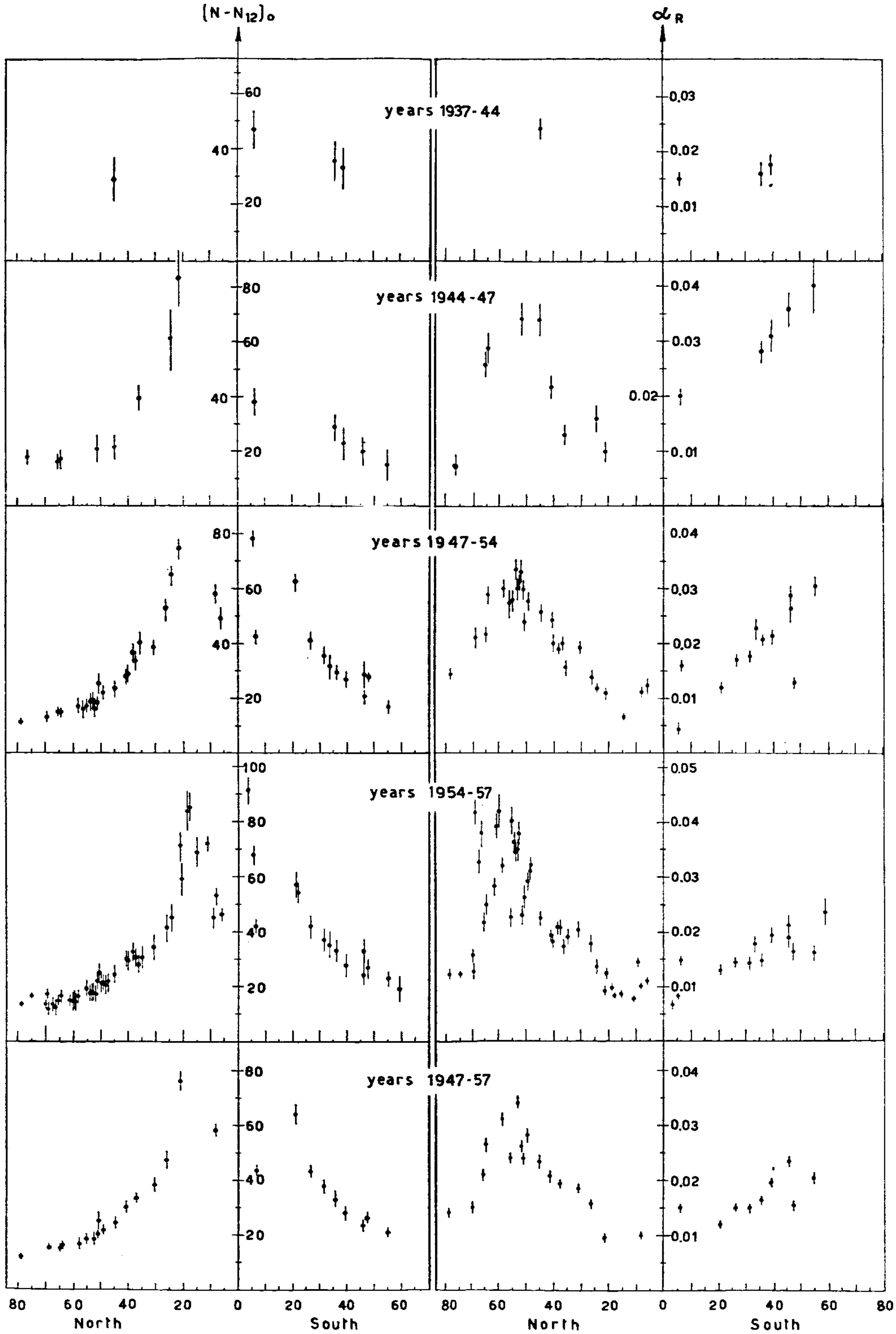

FIG. 5. Correlation of month-to-month variation $N-N_{12}$ and R.

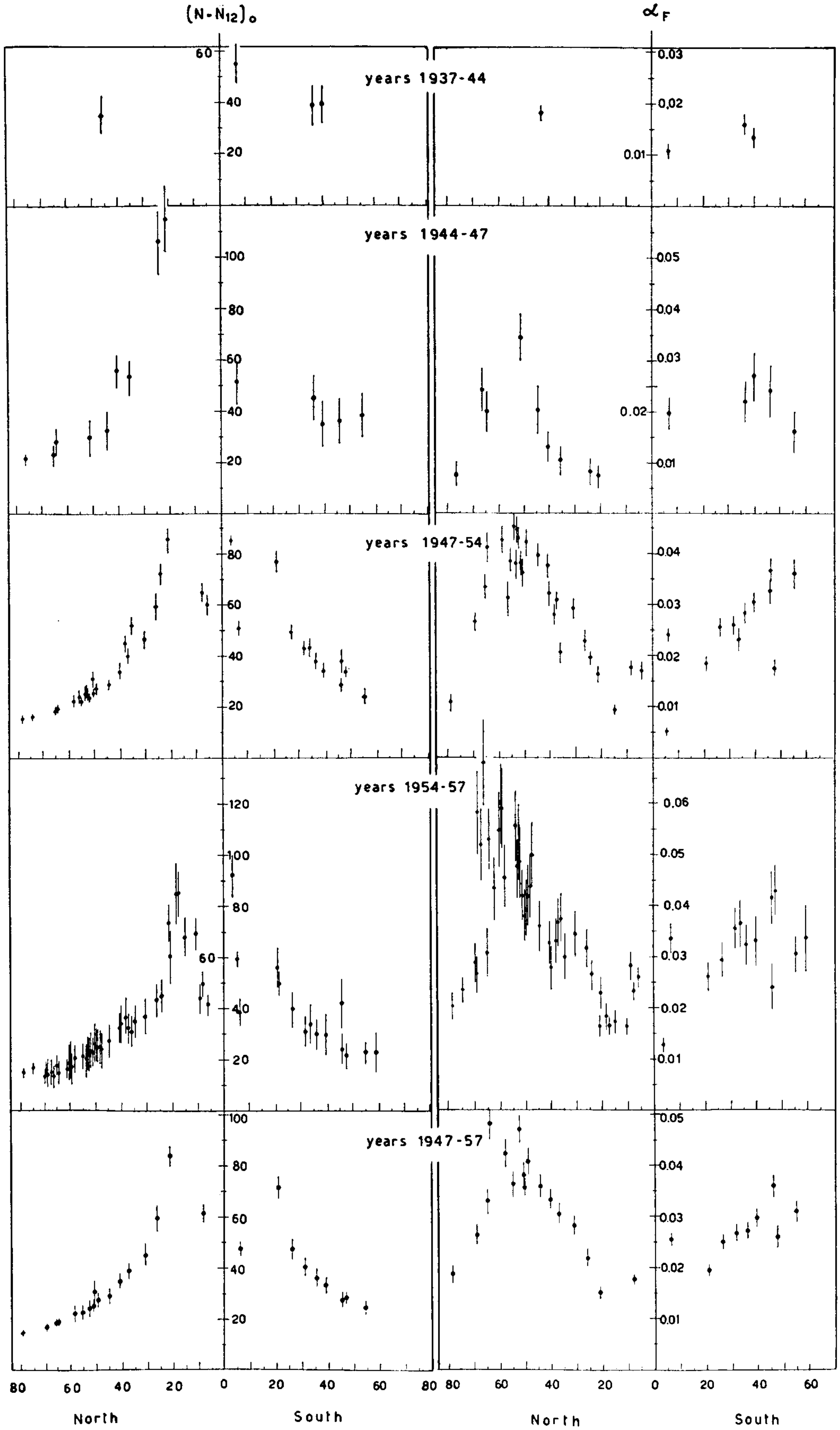

FIG. 6 Correlation of month-to-month variation $N-N_{12}$ and A_F.

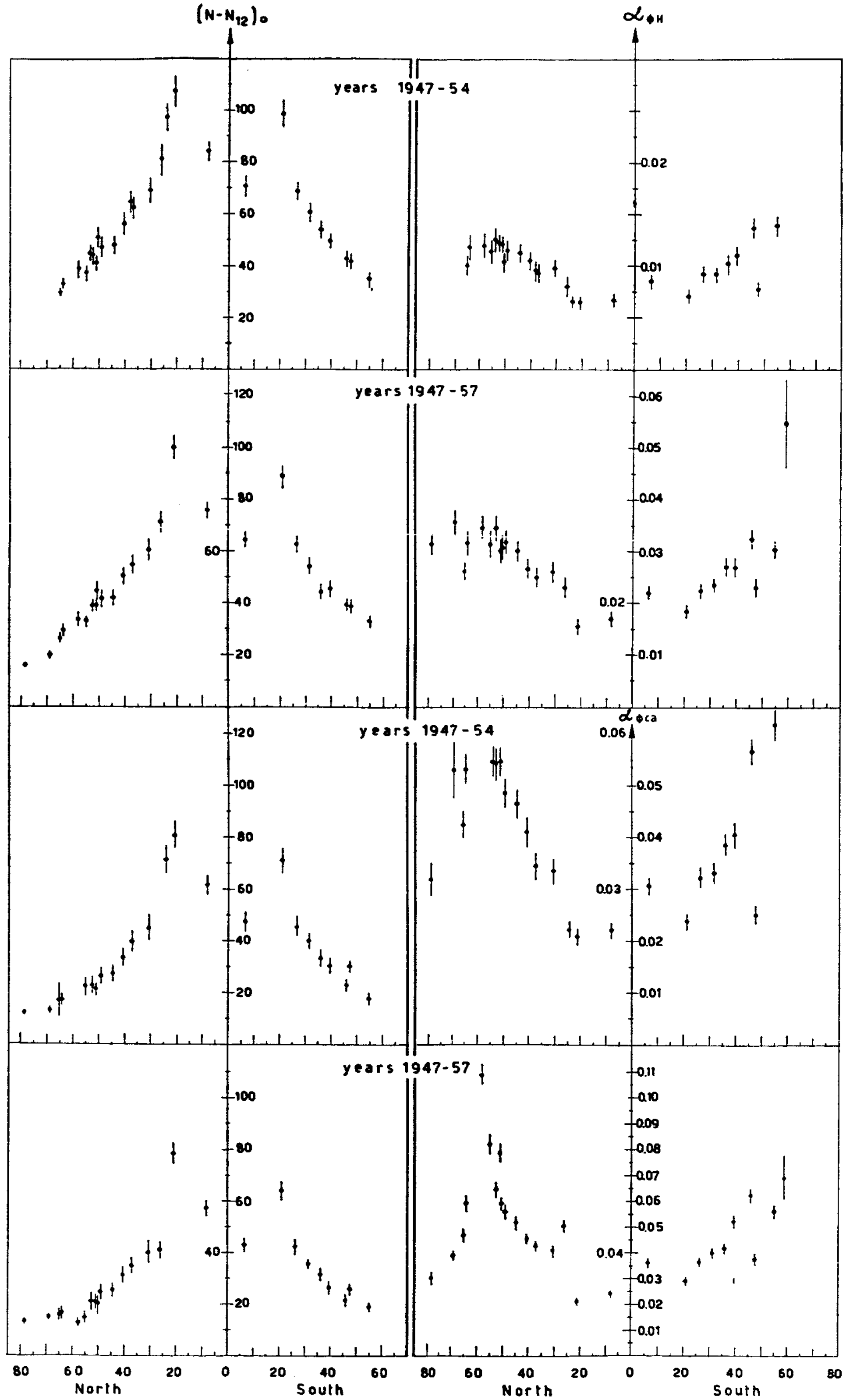

FIG. 7. Correlation of month-to-month variation $N-N_{12}$ and $A\phi_H$ (upper graphs) and $N-N_{12}$ and $A\phi_{Ca}$ (lower graphs).

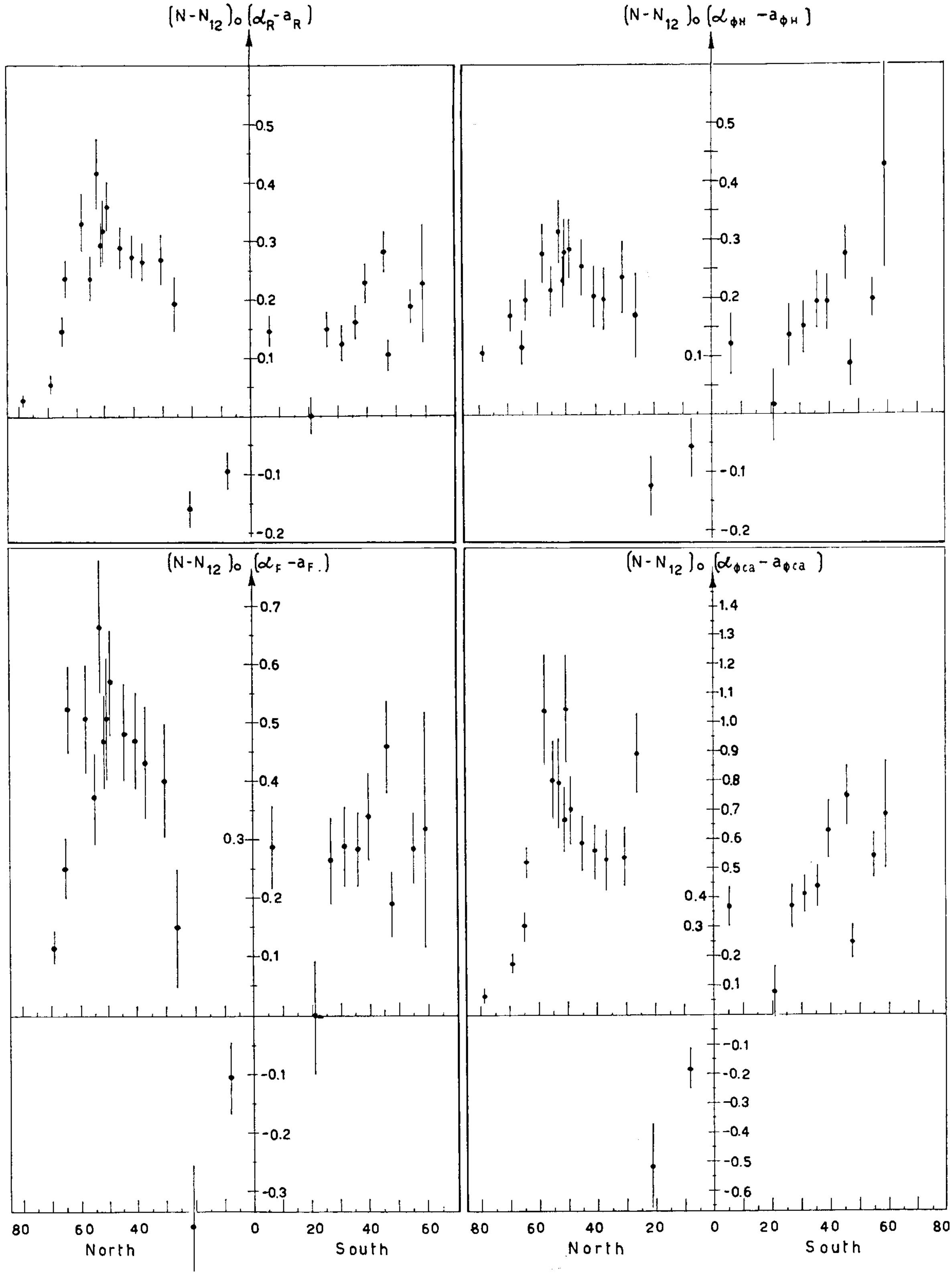

FIG. 8. Latitudinal variation of $(N-N_{12})_0(\alpha_i-a_i)$ for the 11 years 1947–1957. The values at latitude 59S refer to the years 1954–1957.

not the case for the correlations with $A_{\Phi H}$ and $A_{\Phi Ca}$ (Fig. 7).

If we again assume a mean value a_i of α_i for the tropical belt of latitudes, we can write the regression equation (3) in the form

$$N-N_{12}=(N-N_{12})_0[1+a_iA_i+(\alpha_i-a_i)A_i]. \quad (6)$$

Fig. 8 shows the 1947–1957 behavior of $(N-N_{12})_0 \times(\alpha_i-a_i)$ which represents, as we have already seen, an index of the absolute latitudinal effect on the ionospheric electron density.

Although the statistical errors are much greater because of the combination of the errors in $(N-N_{12})_0$ with those in α_i and a_i, the latitudinal effect is clearly enhanced.

For the double correlation defined by (4), however, we again failed to obtain results having some clear physical meaning.

3.3 *Effect of the heliographic latitude of solar disturbances.* In order to look for a dependence of ionospheric electron density on the heliographic latitude of the perturbation centers on the solar disk, we studied the data collected by the observatory of Meudon on filament activity, as a function of heliographic coordinates. Such data are given for each solar rotation period (27 days). We expressed them in terms of terrestrial months by making a weighted mean as follows: if in a terrestrial month there are contained n days of the 27 days of a solar rotation period and m days of the following rotation period, and x and y are the numbers which express the filament activity for the two rotation periods, the mean terrestrial-month activity is defined as $\frac{nx+my}{n+m}$.

We have separately considered the activity of: (i) polar filaments; (ii) equatorial filaments; (iii) filaments between the heliographic latitudes 30N to 30S; (iv) filaments in the northern solar hemisphere; (v) filaments in the southern solar hemisphere. In each case, the correlations do not seem significant; the values of the coefficients of the linear regressions (1) and (3) exhibit noticeable and irregular differences for different observatories; in many cases negative values of $\bar{N}_0$ and $(N-N_{12})_0$ were also obtained.

According to the present investigation, no significant correlation appears to exist between the ionospheric *F2* layer and the latitudinal distribution of solar activity centers.

4. The interpretation of the latitudinal effect

4.1 The "corpuscular" hypothesis. On the basis of the conclusion drawn from the results of Section 3, we give a tentative physical interpretation of the latitudinal effect according to the following hypotheses.

(i) The effect is caused by a corpuscular radiation impinging, with a characteristic latitudinal distribution, upon the upper atmosphere.

(ii) The corpuscular radiation has a rather low mean energy (of the order of kev or tens of kev), so that it reaches the 200-km level, i.e., the *F2* layer, but does not necessarily reach the *E* layer (Mariani, 1957).

(iii) The intensity of the radiation depends (as a first approximation) linearly on the solar activity.

First, we estimate the order of magnitude of the particle flux necessary to give the actual ionization rate. We assume that a particle loses all its energy in the ionization of neutral particles. In the steady state which we may assume for the *F2* layer at noon, we write the equilibrium equation in the form

$$I-bn_e=0, \quad (7)$$

where I is the production rate, b is the effective recombination coefficient, and n_e the electron density. By noting that the maximum values of the ratios $(\alpha_i-a_i)/a_i$ at latitudes of 55–60 deg generally have values between 1 and 2, one concludes that the effects of the variable part of the ultraviolet radiation and that of the corpuscular radiation are comparable. However, the total ultraviolet contribution, proportional to $1+\alpha_iA_i$, becomes more and more important with respect to the corpuscular contribution as the solar activity decreases. At maximum solar activity (a conventional value of the sunspot number R equal to 150) the quantities $1+\alpha_iA_i$ and α_i-a_i are about the same; in this physical situation, the corpuscular ionization rate I_c is comparable to the ionization rate I_u of the ultraviolet radiation.

Thus we have

$$I_u\approx I_c\approx\frac{I}{2}\approx b\frac{n_e}{2}. \quad (8)$$

If we put $b=10^{-4}$ sec^{-1} and $n_e=10^6$ cm^{-3} (so that the ionospheric layer has a critical frequency $f_c\approx 9$ Mc sec^{-1}), we obtain, at the height of maximum electron density (300–350 km):

$$I_u\approx I_c\approx 50 \text{ ions cm}^{-3}\text{ sec}^{-1}.$$

We now make use of the fact that the photoionization rate at heights more than 300 km decreases exponentially (Watanabe and Hinteregger, 1962). We assume that above this altitude 50 per cent of the ionization is due to corpuscular radiation. Thus an estimate of the total corpuscular ionization in a square cm column of air above 300 km at middle latitudes can be $I_{\text{total}}\approx 2\times 10^9$ ions cm^{-2} sec^{-1}. If the mean ionization loss is 35 ev/ion-pair, the corresponding kinetic energy flux is $F_T\approx 7\times 10^{10}$ ev cm^{-2} sec$^{-1}\approx 0.1$ erg cm^{-2} sec^{-1}. For comparison, the total energetic flux entering the atmosphere, assuming the solar constant$=2$ cal cm^{-2} min^{-1} is 1.4×10^6 erg cm^{-2} sec^{-1}.

The above data allow a simple evaluation of the order of magnitude of the required particle flux. If the particles can penetrate vertically to a minimum altitude of 150 km, they have, if they are electrons, a kinetic energy $T\approx 1500$ ev. However, the effect of scattering and of the geomagnetic field is that the path of the electrons is not a vertical straight line. On the average, then, they stop at higher altitudes, i.e., in the F layer. The total incoming electron flux F_e, at maximum solar activity, can be estimated as

$$F_e = \frac{F_T}{1500} \approx 5 \times 10^7 \text{ electrons cm}^{-2}\text{ sec}^{-1}.$$

The velocity of an electron having an energy $T \approx 1500$ ev is $v \approx 2.3 \times 10^9$ cm sec^{-1} so that the particle density in the incoming stream is of the order of 10^{-2} cm^{-3}.

If such a corpuscular radiation impinges uniformly on the upper atmosphere between the latitudes of 30 deg and 65 deg (a surface of $\frac{1}{3}$ of the total area of the earth), the total incoming flux is of the order of 10^{26} electrons sec^{-1}. In view of this intensity, it does not seem possible to attribute such a flux of electrons to a primary source other than the sun. On the other hand, the particular features of the latitudinal effect exclude the possibility that they are coming directly from the sun along Störmer trajectories. As mentioned earlier, we may however assume that the electrons are leaking from the Van Allen radiation belts.

We may also consider the low-energy electron fluxes measured by Krasovskii *et al.* (1962) and, more recently, by O'Brien (1962). Krasovskii reports that at 45 deg geomagnetic latitude an energy flux of dumped electrons of energy $T \approx 10$ kev between 10^{-2} and 1 erg cm^{-2} sec^{-1} was observed during one pass of Sputnik 3. The more systematic measurements of O'Brien, made on Injun I, gave median fluxes of 10^6 trapped electrons cm^{-2} sec^{-1} with $T \geq 40$ kev. Corresponding to these intensities, O'Brien reports average energy fluxes of trapped electrons with $T \geq 1$ kev of the order of 1 to 10 erg cm^{-2} sec^{-1}. We notice that the above assumed electron energy of 1.5 kev is just the average energy if we assume, for energy ≥ 1 kev, a power law differential spectrum with an exponent $\gamma = 4$. Thus, the number fluxes of trapped electrons with mean energy $T = 1.5$ kev are of the order of 5×10^9 cm^{-2} sec^{-1}. With "lifetimes" of 10^3 to 10^4 sec, as calculated by O'Brien for particles with $T > 40$ kev, one computes dumped electron fluxes of not less than 10^5 to 10^6 cm^{-2} sec^{-1}; the corresponding energy fluxes are not less than 10^{-4} to 10^{-3} erg cm^{-2} sec^{-1}.

If one considers that the measurements of O'Brien have been made in a period of reduced solar activity ($R = 50$) and that the "lifetime" of very low-energy electrons may be substantially lower than that estimated for electrons with $T > 40$ kev, we can effectively consider the dumped electron flux from Van Allen belts as an important source (or *the* source) of the corpuscular radiation in the $F2$ layer.

Some difficulty could arise here from the fact that the corpuscular ionospheric effect decreases very sharply at latitudes higher than 60 deg, while in practice the electron fluxes measured by O'Brien are nearly constant at all latitudes up to 70 deg, corresponding to a maximum geocentric distance of about 10 earth radii. Concerning this point, we must bear in mind, however, that our results concern the state of the ionosphere averaged with respect to the solar cycle. One cannot exclude some small year to year shift of the latitude of maximum corpuscular effect, in particular toward lower latitudes as solar activity decreases. If this is the case, one can reasonably assume that at maximum solar activity the maximum corpuscular effect may occur at higher geomagnetic latitudes, 60 to 65 deg or even higher.

A further quantitative element we can easily calculate is the integrated flux of particles during the entire eleven-year solar cycle. If we assume a linear long-term time variation, and remember that the above calculated flux values refer to the maximum solar activity, we estimate that the integrated electron flux entering the upper atmosphere may be 10^{34} electrons. The corresponding integrated energy, assuming a mean energy of kevs, is 10^{25} to 10^{26} ergs.

One immediately sees that the above integrated fluxes of particles and energy represent only a very small part of the fluxes ultimately emitted from the sun during its full cycle of activity.

4.2 Other evidence for corpuscular effects and conclusions. Finally, we want to draw attention to the many experimental indications of intensive particle fluxes in the upper atmosphere. It is agreed that polar aurorae are the result of corpuscular radiation, although the origin is not fully understood.

Antonova and Ivanov-Kholodny (1961) point out the possibility of a corpuscular origin of nighttime ionospheric ionization; their calculated flux of electrons of about 100 ev would be 10^{10} to 10^{11} electrons cm^{-2} sec^{-1}, to which corresponds an energy flux of 1 to 10 erg cm^{-2} sec^{-1}. These electron and energy fluxes are 10^3 to 10^4 higher than our minimum estimates. Such high fluxes, based on the assumption of a high value of the loss coefficient in the $F2$ layer (10^{-7} to 10^{-6} cm^3 sec^{-1}) are probably overestimated, since the actual coefficient appears to be much smaller.

Several experimental results (Bourdeau and Bauer, 1962) indicate that, at altitudes approximately between 150 and 350 km, the electron temperature is higher than the ion temperature. Bourdeau (1962) also points out that "large fluxes of quasi-energetic particles which could provide an additional ionization source have been observed at some geographical locations in the upper atmosphere."

Harris and Priester (1962), in their calculated theoretical models for the solar-cycle variation of the upper atmosphere, assume an ultraviolet heat source and a corpuscular heat source, of almost equal magnitude, of the order of 1 erg cm^{-2} sec^{-1}. Contrary to our scheme, however, the assumed ratio between corpuscular and ultraviolet fluxes does not vary during a solar cycle.

We conclude that if the electron flux calculated in Section 4.1 is really present in the $F2$ layer, it could possibly originate in the radiation belts; in any case the Van Allen belts are a good reservoir of ionospheric ionizing particles. This possibility obviously does not exclude some other acceleration mechanism acting on very low-energy electrons "normally" present in the upper atmosphere: for example, one could think in terms of an electric field, present only (or mainly) in the latitude range in which the "corpuscular effect" is present. From a general point of view, it will be very interesting to study the eventual dependence of the corpuscular effect on local time, as has been done for the polar aurora. Actually, the experimental parameter, the *F2* layer critical frequency, is a more or less approximate index of ultraviolet and corpuscular radiation only near noon; at other times, particularly during the night, it is controlled primarily by other phenomena as time and height variations of recombination or attachment coefficients, temperature variations, convective motions, etc., so that it cannot be considered an even approximative index of the incoming corpuscular radiation. At present, the first and more immediate experimental problem would be the *direct* detection of very low-energy particle flux at ionospheric levels; we hope that this can be done in the near future.

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